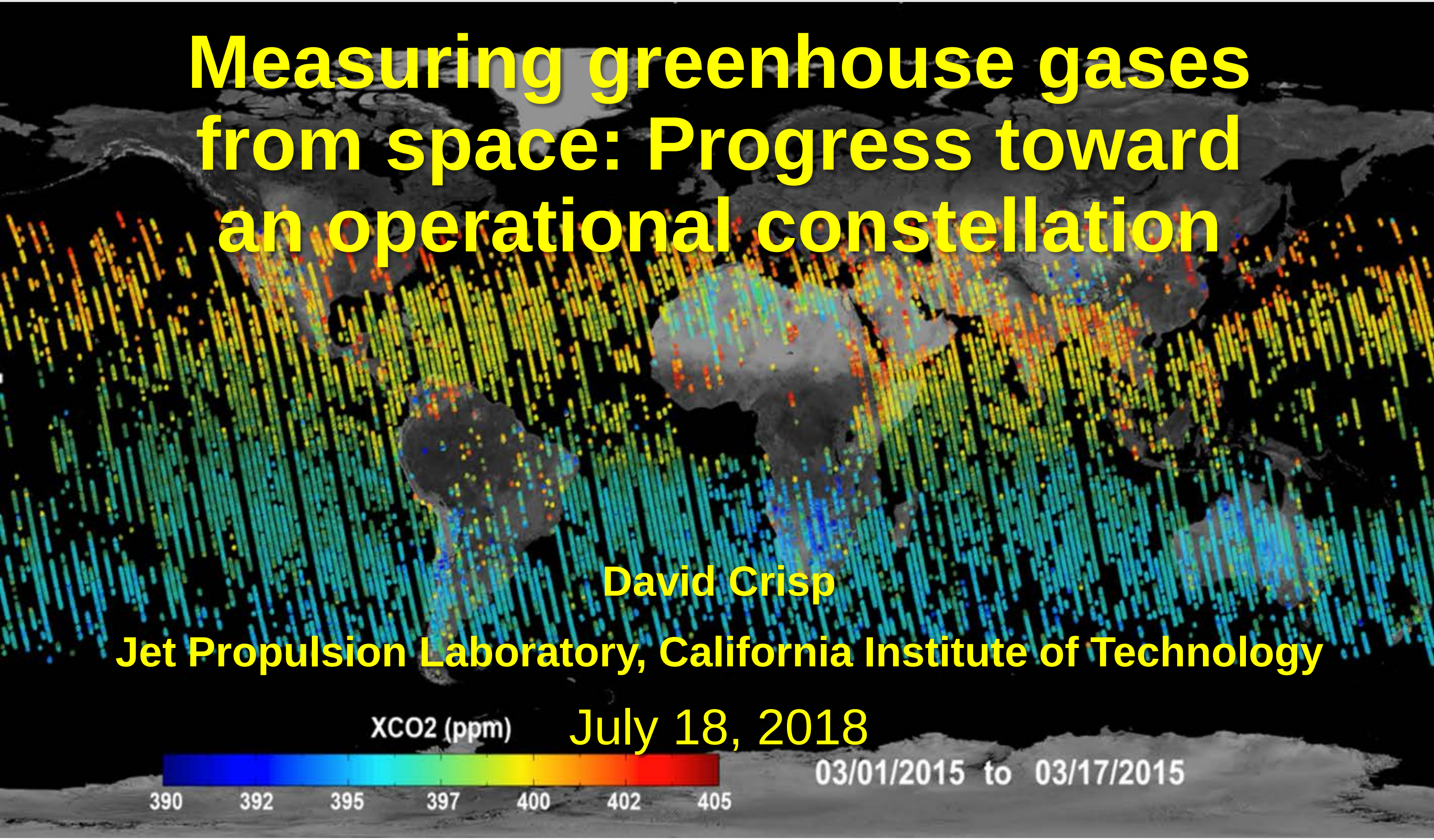
COSPAR 2018

Measuring greenhouse gases from space: Progress toward an operational constellation

David Crisp

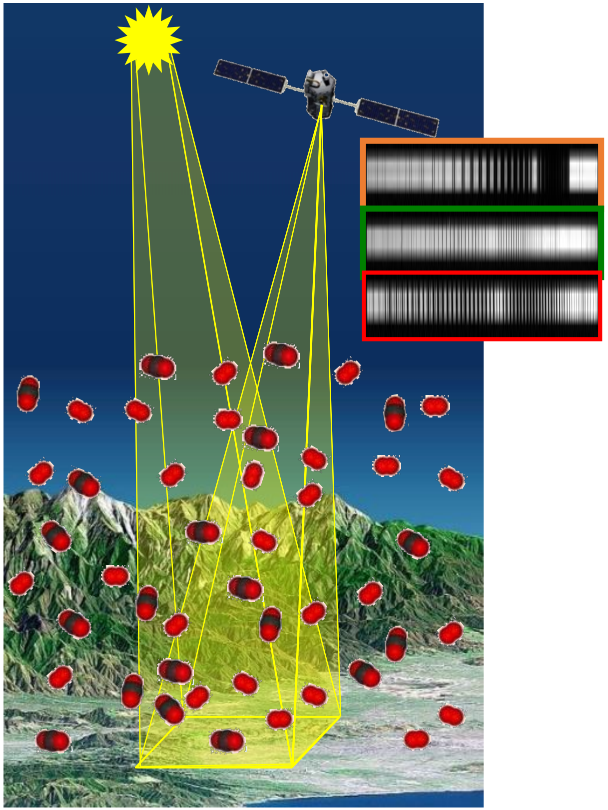
Jet Propulsion Laboratory, California Institute of Technology

July 18, 2018

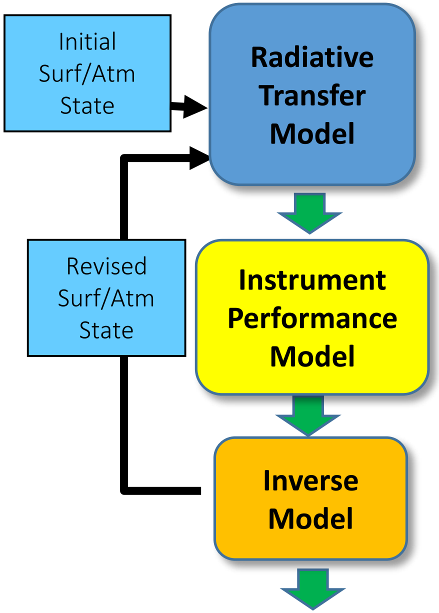


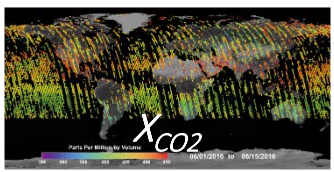
Measuring CO_2 and CH_4 from Space

- **Record** spectra of CO_2, CH_4, and O_2 absorption in reflected sunlight



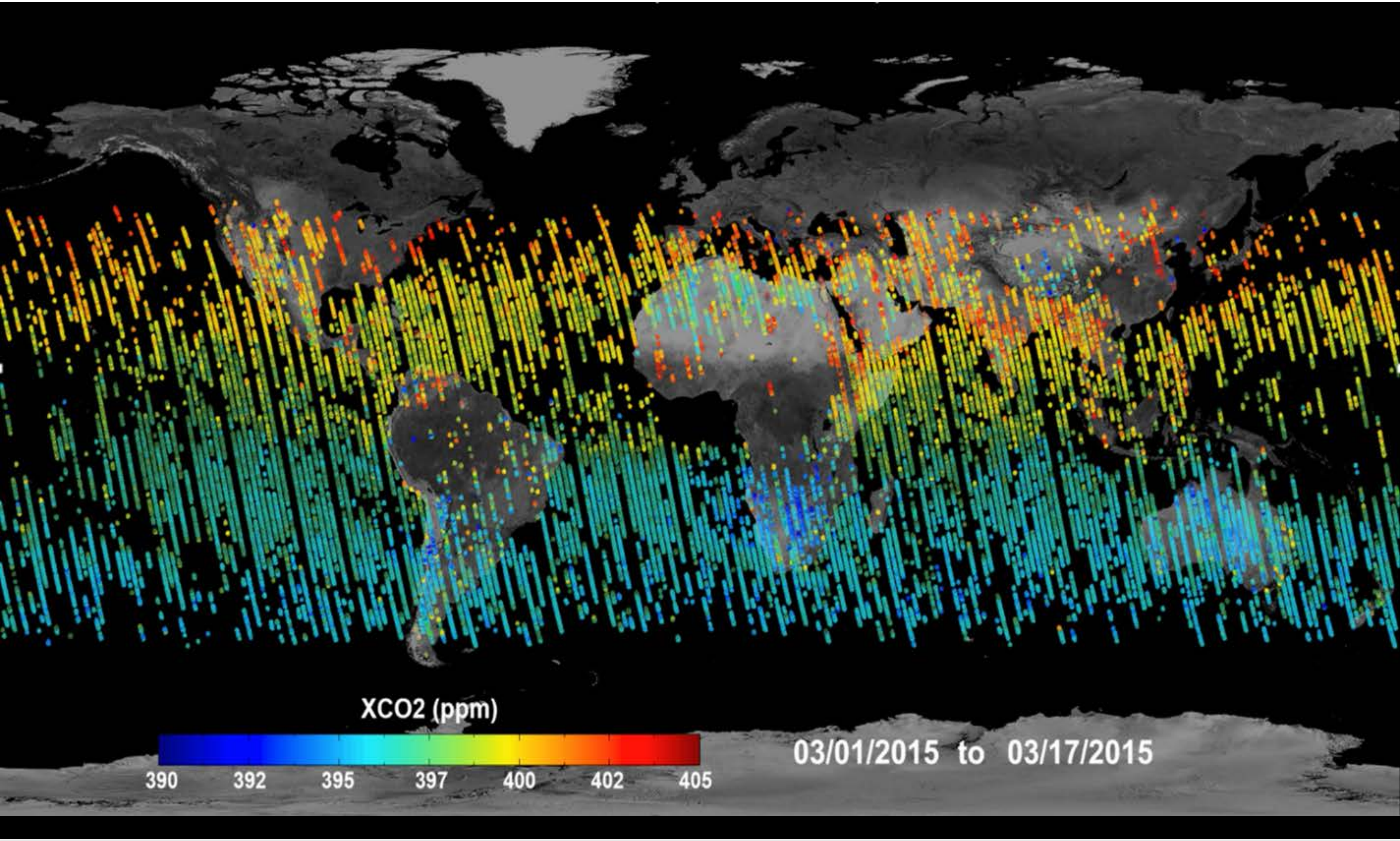
Retrieve variations in the column averaged dry air mole fraction, X_{CO2}, X_{CH4} over the sunlit hemisphere



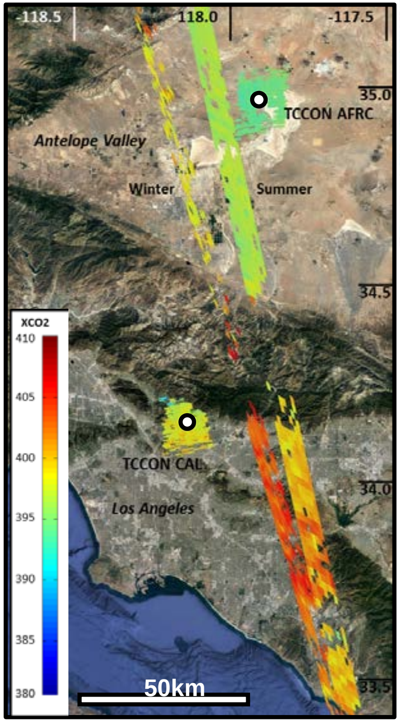


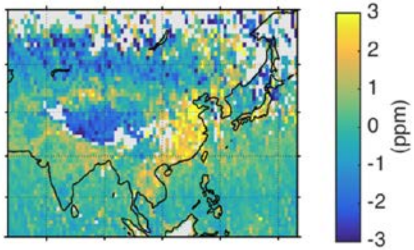
Validate measurements to ensure X_{CO2} and X_{CH4} accuracy of ~0.25%

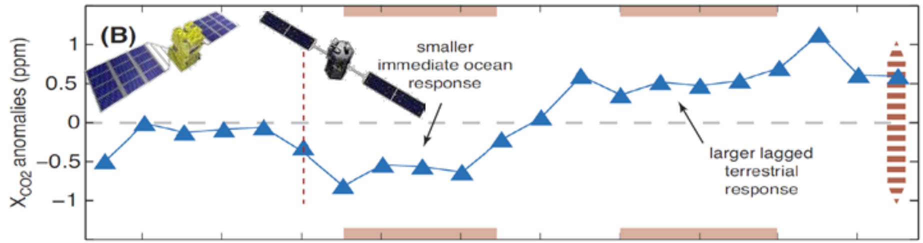
Collecting Space-based X_{CO2} Measurements



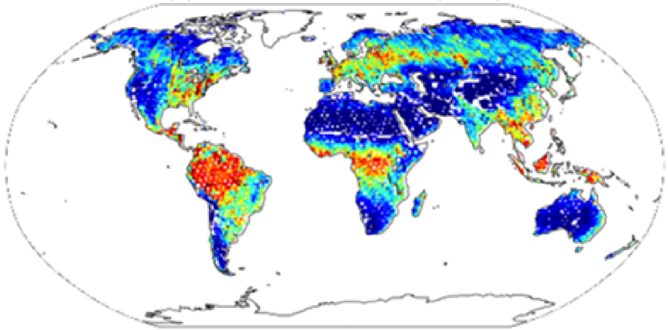
These Systems are Now Being Used to Study the Carbon Cycle



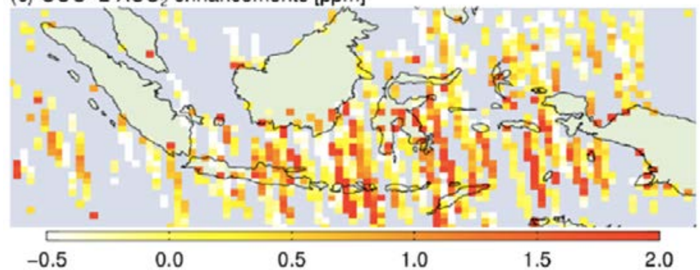




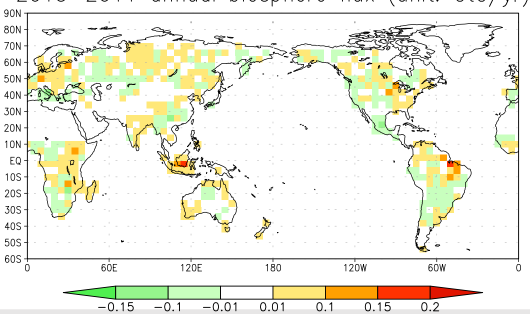
(a) OCO-2 SIF @757nm (2015)

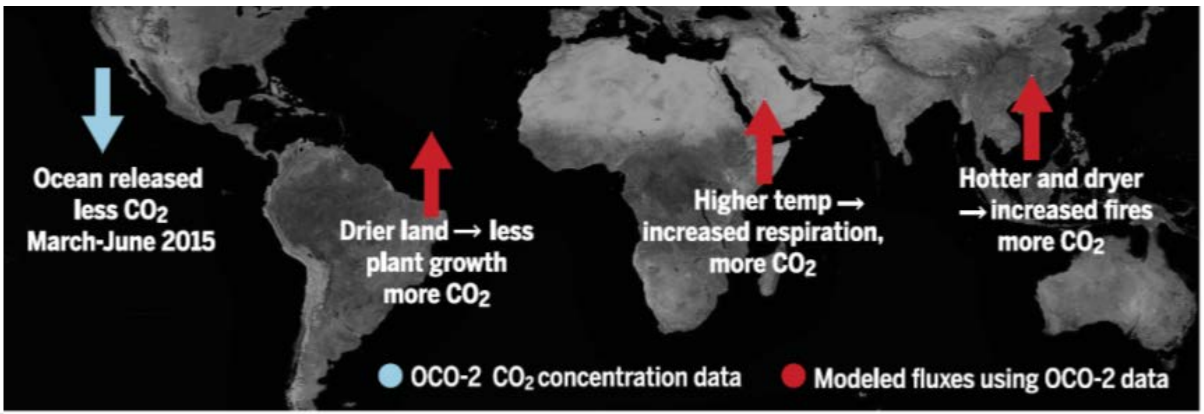


(c) OCO–2 XCO_2 enhancements [ppm]



2015–2011 annual biosphere flux (unit: GtC/yr)



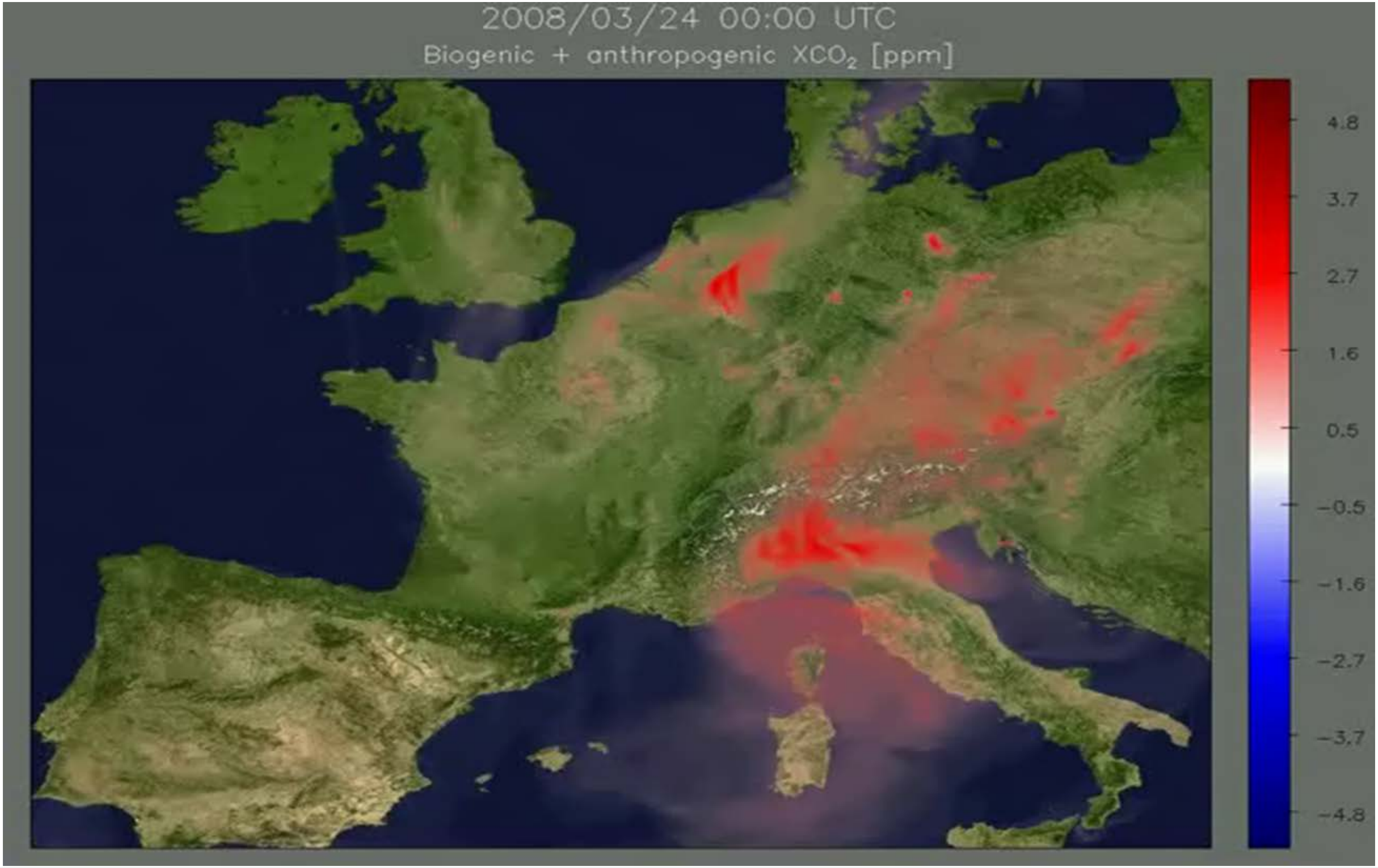


Fast Forward to 2015: COP21

To support the Paris Agreement:

- The overall goal is to develop a sound, scientific, measurement-based approach that:
  - reduces uncertainty of national emission inventory reporting,
  - identifies large and additional emission reduction opportunities
  - provides nations with timely and quantified guidance on progress towards their emission reduction strategies and pledges (Nationally Determined Contributions, NDCs)
- In support of these efforts, atmospheric measurements of greenhouse gases from satellites could
  - Improve the frequency and accuracy of inventory updates for nations not well equipped for producing reliable inventories, and
  - help to "close the budget" by measurement over ocean and over areas with poor data coverage
- We now have strong support, but new marching orders

Anthropogenic Emissions

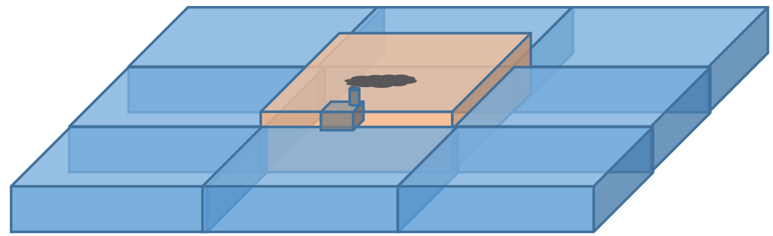


Compact Source Uncertainties Drive Measurement Precision

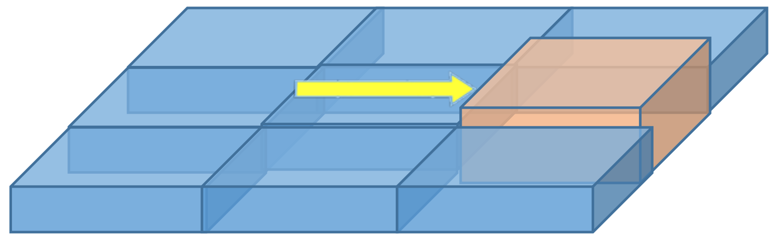
- For emission sources that are smaller than the footprint size, the minimum detectable mass or mass change depends on instrument precision (ΔX_{CO2} or ΔX_{CH4}) and footprint area, A.
- The minimum detectable flux change depends on precision, the effective wind speed at the emission level and the footprint's cross section in the direction of the prevailing winds.

$$F_{min} = 2 \cdot u \cdot \Delta M_{CO2}(\Delta XCO2_{min}) / L$$

- Detection limits increase with random error, footprint size, and wind speed



ΔM (1ppm X_{CO2}) = 0.016 kT/km^2

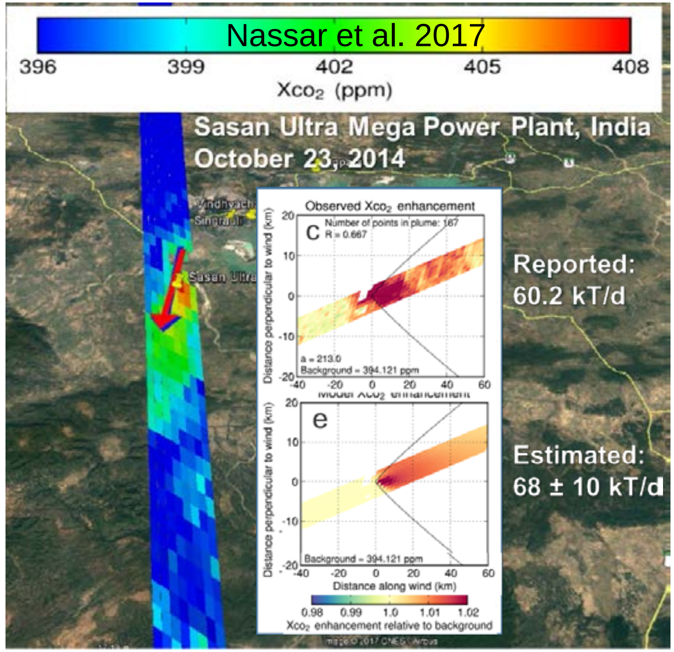


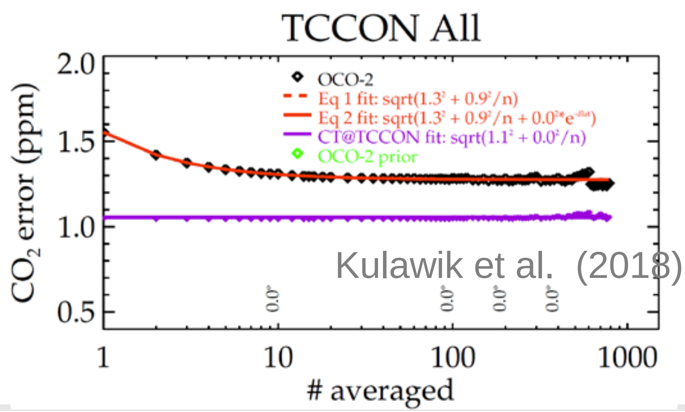
Flux (MTCO$_2$ /year) vs Footprint area and single sounding precision for a 5 km/hour wind

	DXCO2(ppm)				
Area (km^2)	0.25	0.5	1	2	4
1	0.341	0.683	1.37	2.7	5.47
2	0.483	0.966	1.93	3.86	7.73
4	0.685	1.37	2.7	5.47	10.9
10	1.08	2.16	4.33	8.66	17.3
50	2.41	4.83	9.66	19.3	38.6
85	3.14	6.29	12.6	25.1	50.4
1800	14.4	28.9	57.8	115	231

Emissions from Compact Sources: plume models

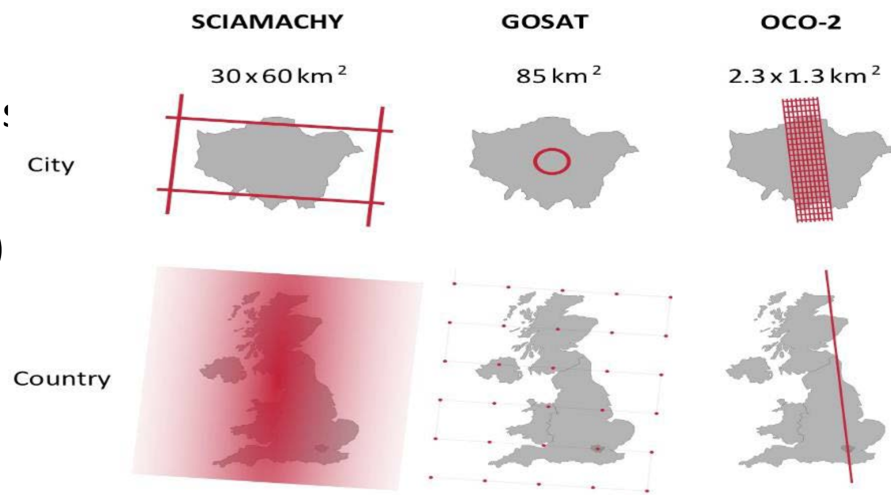
- The OCO-2 (0.5 ppm single sounding random errors) can clearly detect plumes that fall along its ground track
- Plume imaging methods can exploit information from multiple footprints to reduce uncertainties if
  - biases are not spatially correlated
  - footprints within the plume can be discriminated from the background
    - Proxies (NO_2, CO) help for CO_2 plumes
- Averaging typically reduces X_{CO2} anomaly uncertainties (and thus flux uncertainties) by less than a factor of 2
- Wind speed and X_{CO2} uncertainties contribute similar flux uncertainties





Resolution and Coverage: Sampling Strategy

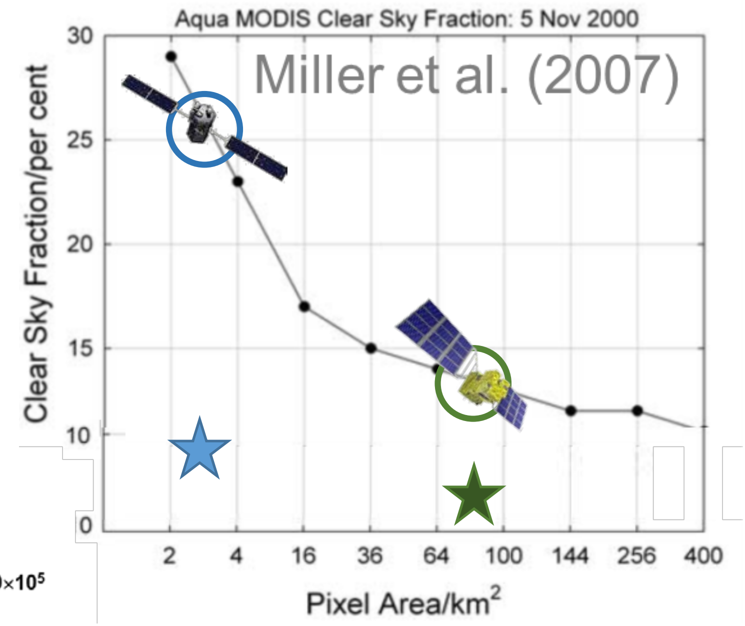
- The resolution and coverage of space based greenhouse gas observations is limited by the spatial sampling strategy adopted
  - The large (30 km x 60 km) footprints used by SCIAMACHY provided good coverage of the Earth, but many footprints were contaminated by clouds
  - Systems that collect spatially-isolated sample (GOSAT, Feng Yun 3D, Gaofen-5) cannot resolve localized emissions (plumes) as well as their background
  - Continuous “stripes” (OCO-2, TanSat, and MicroCarb) provide high spatial resolution along a narrow track but large gaps between sample tracks

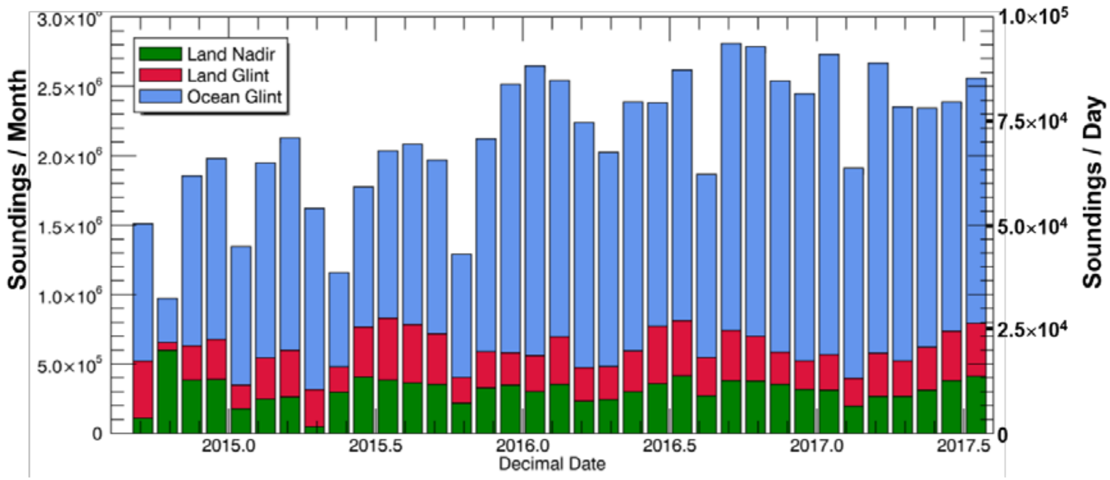


- Systems that cannot observe the glint spot over the full range of latitudes cannot collect observations over the oceans, which cover 70% of the surface of the Earth
- Passive solar systems can only collect observations while the sun is up

Resolution and Coverage: Clouds!

- Early in the evolution of the OCO and GOSAT missions, optically thick clouds were identified as significant limitation on coverage
- Based on MODIS cloud studies, a small footprint was adopted for OCO (and OCO-2) to mitigate this issue
- Actual yields are worse than expected

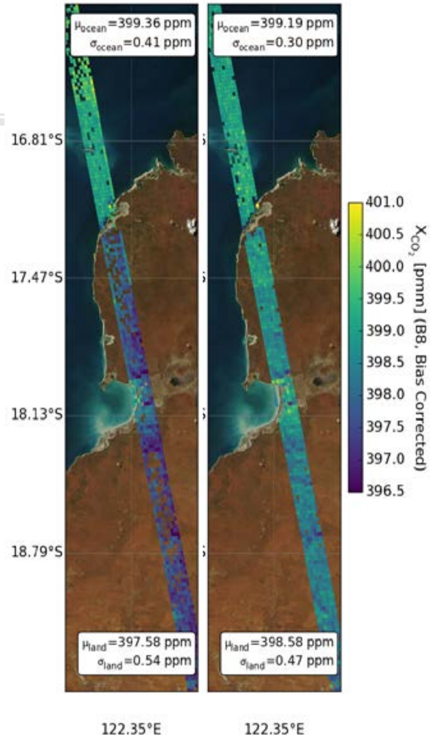


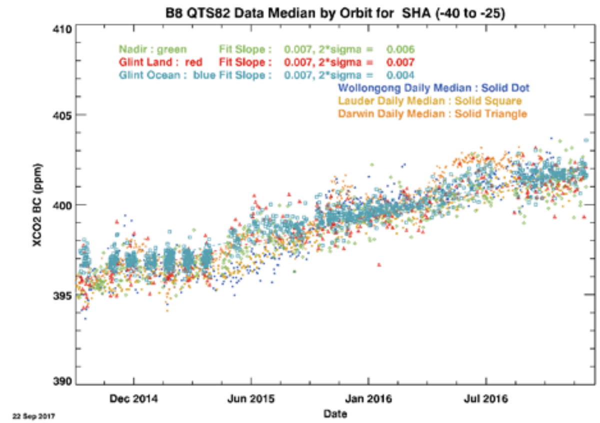


The majority of the clear soundings collected by OCO-2 are collected over the ocean by observing the ocean “glint spot”

Mitigating the Impact of Biases

- Fortunately, only spatially and temporally coherent biases operating on the scale of interest can introduce flux errors as large as the one illustrated on the previous slide
    - Biases that are spatially and temporally invariant do not introduce large flux errors, because fluxes are proportional to the product of the anomaly amplitude and the wind, $F \propto u \times \Delta X_{CO2}$
    - Small scale biases often average out
- Some processes can introduce spatially coherent biases
    - surface pressure, air mass dependence, optically-thin clouds and/or aerosols, surface albedo, ...)
- Many of these processes can be identified and mitigated through a well designed calibration/validation program





Missions: The Pioneers

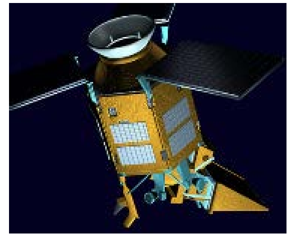
- **SCIAMACHY (2002-2012)** – First sensor to measure O_2, CO_2, and CH_4 using reflected NIR/SWIR sunlight
    - Regional-scale maps of X_{CO2} and X_{CH4} over continents
- **GOSAT (2009 …)** – First Japanese GHG satellite
    - FTS optimized for high spectral resolution over broad spectral range, yielding CO_2, CH_4, and chlorophyll fluorescence (SIF)
- **OCO-2 (2014 …)** – First NASA satellite to measure O_2 and CO_2 with high sensitivity
    - High resolution imaging grating spectrometer small (< 3 km^2) footprint and rapid sampling (10^6 samples/day)
- **TanSat (2016 …) -** First Chinese GHG satellite
    - Imaging grating spectrometer for O_2 and CO_2 bands and cloud & aerosol Imager

The Next Generation

In orbit Checkout

- **Feng Yun 3D (2017)** – Chinese GHG satellite on an operational meteorological bus
  - GAS FTS for O_2, CO_2, CH_4, CO, N_2O, H_2O

- **Sentinel 5p (2017)** - Copernicus pre-operational Satellite
  - TROPOMI measures O_2, CH_4 (1%), CO (10%), NO_2, SIF
  - Imaging at 7 km x 7 km resolution, daily global coverage



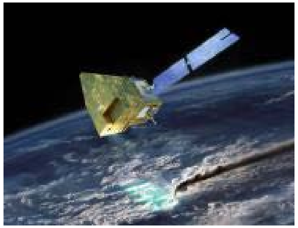
- **Gaofen 5 (2018)** - 3rd Chinese GHG Satellite
  - Spatial heterodyne spectrometer for O_2, CO_2, and CH_4

- **GOSAT-2 (2018)** – Japanese 2nd generation satellite
  - CO as well as CO_2, CH_4, with improved precision (0.125%), and active pointing to increase number of cloud free observation

- **OCO-3 (2019)** – NASA OCO-2 spare instrument, on ISS
  - First CO_2 sensor to fly in a low inclination, precessing orbit

Future GHG Satellites

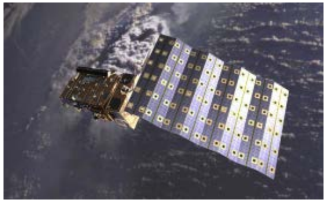
- **CNES/UK MicroCarb (2021+)** – compact, high sensitivity
  - Imaging grating spectrometer for O_2 A, O_2 $^1\Delta_g$, and CO_2
  - ~1/2 of the size, mass of OCO-2, with 4.5 km x 9 km footprints



- **CNES/DLR MERLIN (2022+)** - First CH_4 LIDAR (IPDA)
  - Precise (1-2%) X_{CH4} retrievals for studies of wetland emissions, inter-hemispheric gradients and continental scale annual CH_4 budgets

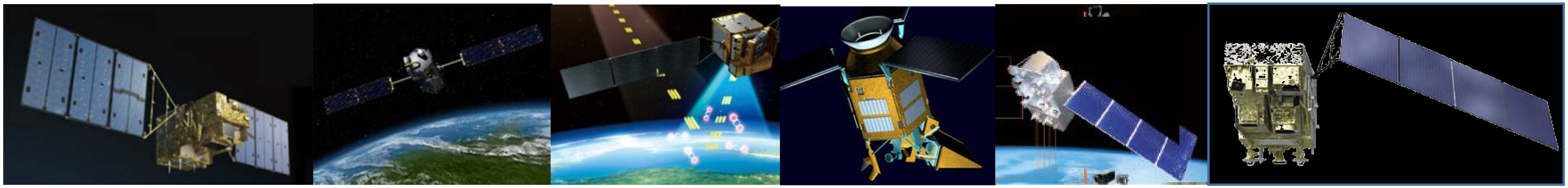
- **NASA GeoCarb (2022*) – First GEO GHG satellite**
  - Imaging spectrometer for X_{CO2}, X_{CH4}, X_{CO} and SIF
  - Stationed above 85° W for North/South America

- **Sentinel 5A,5B,5C (2022) - Copernicus operational services for air quality and CH_4**
  - Daily global maps of XCO and XCH4 at < 8 km x 8 km

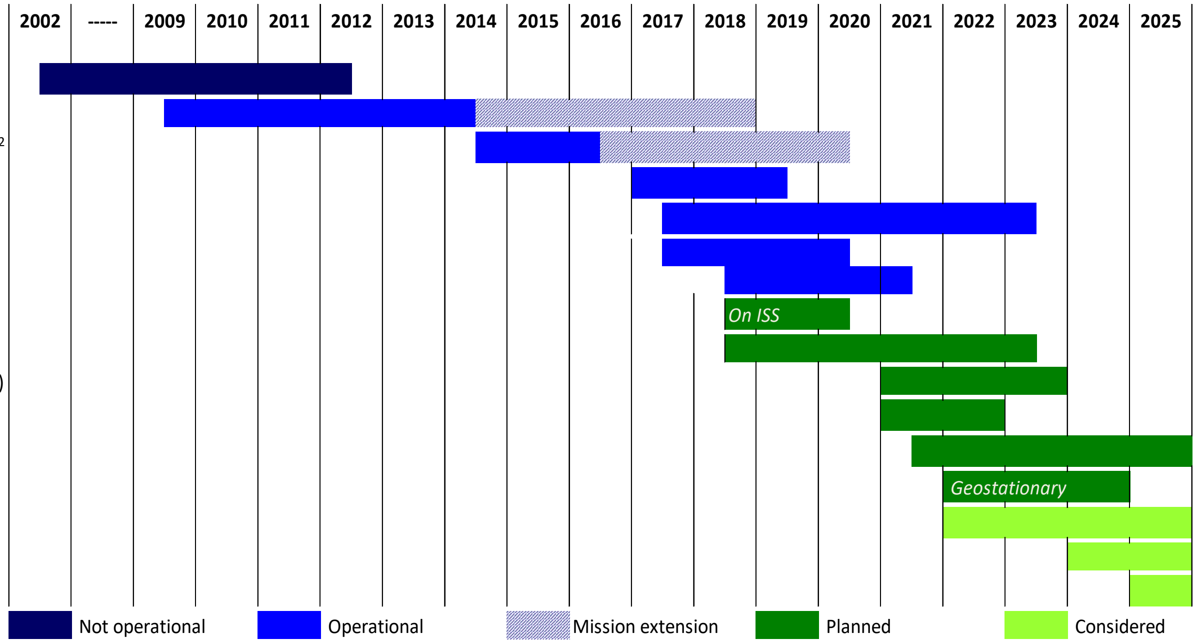


" Pre-Decisional Information -- For Planning and Discussion Purposes Only

Improving Resolution and Coverage: Combining Data from the Emerging Fleet



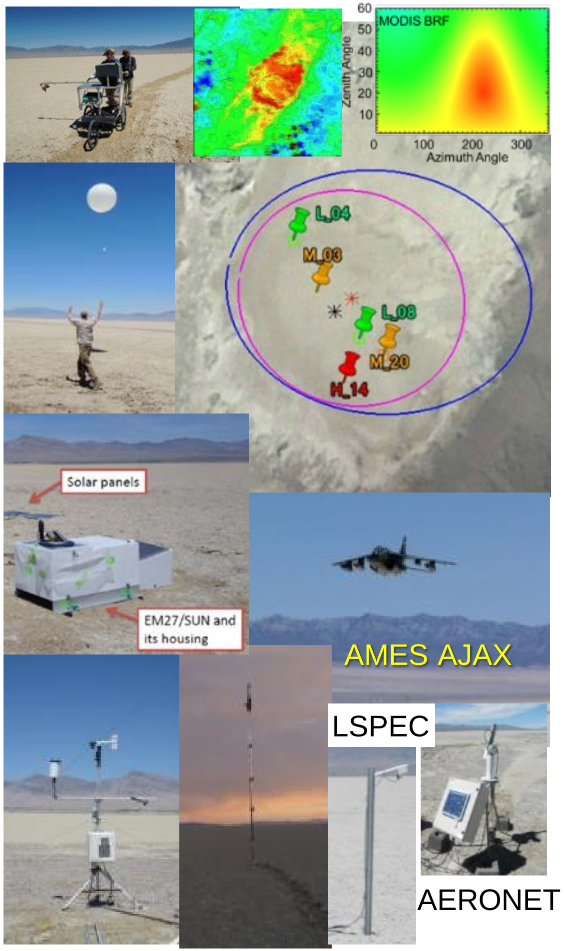
Satellite, Instrument (Agencies)	CO_2	CH_4	Swath	Sample
ENVISAT SCIAMACHY (ESA)	●	●	960 km	30x60 km^2
GOSAT TANSO-FTS (JAXA-NIES-MOE)	●	●	3 pts	10.5 km (d)
OCO-2 (NASA)	●		10.6 km	1.3x2.3 km^2
TanSAT (CAS-MOST-CMA)	●		20 km	1x2 km^2
Sentinel 5P TROPOMI (ESA)		●	2600 km	7x7 km^2
Feng Yun 3D GAS (CMA)	●	●		10 km (d)
GaoFen-5 GMI	●	●		10 km (d)
OCO-3 (NASA)	●		11 km	~4 km^2
GOSAT-2 TANSO-FTS (JAXA-MOE-NIES)	●	●	5 pts	10.5 km (d)
MERLIN (DLR-CNES)		●	100 m	0.14 km (w)
MicroCarb (CNES)	●		13.5 km	40 km^2
MetOp Sentinel-5 series (Copernicus)		●	2670 km	7x7 km^2
GEOCARB (NASA)	●	●		4x4 km^2
Feng Yun 3G (CMA)	●	●		1x1 km^2
GOSAT-3 (JAXA-MOE-NIES)	●	●		
CO2 Monitoring series (Copernicus)	●	●		2x2 km^2



- We could improve resolution and coverage of these satellites by integrating them into a virtual constellation and combining their results

Creating a Combined Data Product: the OCO-2/GOSAT Collaboration

Vicarious Calibration



Retrieval Algorithm

Forward Radiative Transfer Model
Spectra + Jacobians

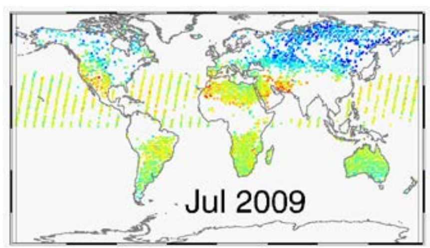
Instrument Model
Spectral+Polarization

Inverse Model
- Compare obs. & simulated spectra
- Update State Vector

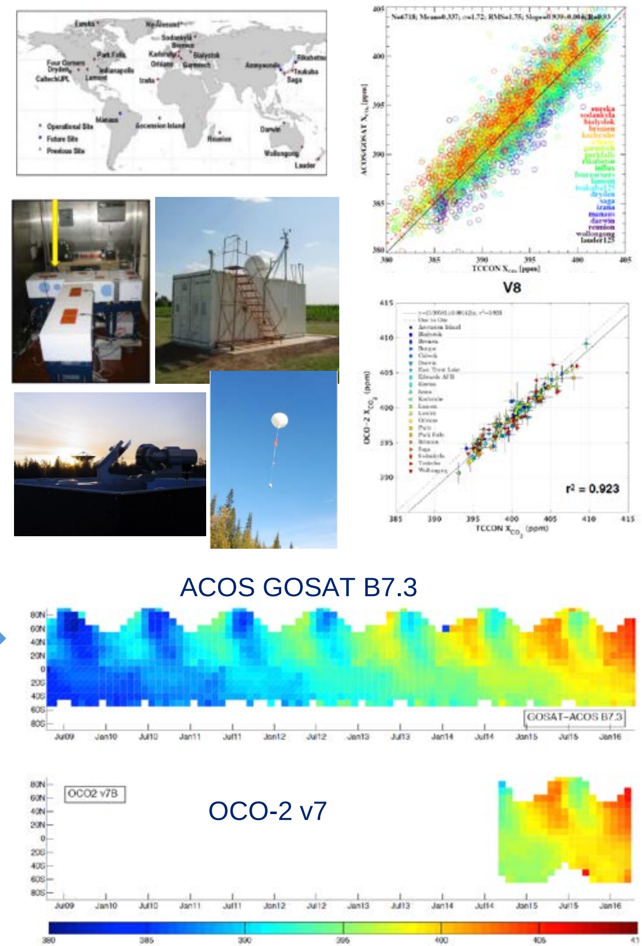
not converged

?

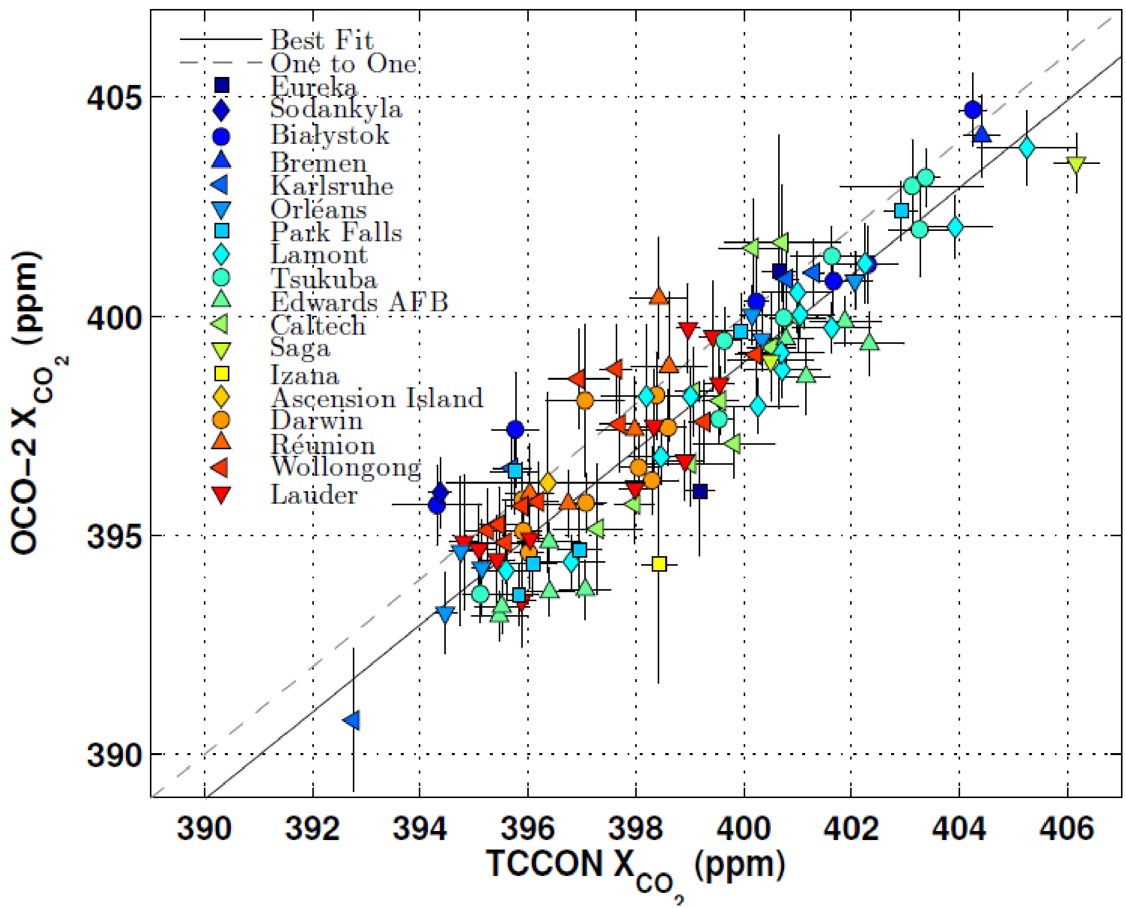
converged



Cross Validation



Validation of X_{CO2} Products Against International Standards: TCCON



Comparisons with the Total Carbon Column Observing Network (TCCON) stations are being used to identify and correct biases in target observations.

After applying a bias correction

- **Global bias is reduced to < 1 ppm**
- **Station-to-station biases reduced to ~1.5 ppm**

Wunch et al. (2016)

Tools Needed to Meet New Requirements

- Sensors with improved precision, spatial resolution, and coverage
  - Improved instrument calibration accuracy and stability
  - Add hoc constellation consisting of the satellites in the “program of record”
  - Dedicated LEO and Geo GHG constellations
- Improved remote sensing retrieval algorithms
  - More accurate description of gas absorption and aerosol scattering
  - Optimized to more fully exploit the information content of solar GHG spectra
- More comprehensive and accurate validation standards
  - Expand and improve ground based in situ, TCCON, AirCore/Aircraft
- Improved atmospheric inversion models for CO_2 and CH_4 fluxes
  - Higher spatial resolution
  - More accurate description of both horizontal and vertical transport
  - More complete assimilation of ground-based, aircraft, and space based data
  - Methods to validate estimated fluxes on local, national, and regional scales

A Candidate GHG Constellation Architecture

The coverage, resolution, and precision requirements could be achieved with a constellation that incorporates the following:

- Coverage and spatial resolution: To cover the globe on bi-weekly intervals, a constellation of ≥ 3 satellites in LEO with
  - Broad (> 200) km swaths with a mean footprint size < 4 km^2
  - Single sounding random error < 0.5 ppm, and vanishing small regional bias (< 0.1 ppm) over > 80% of sunlit hemisphere
  - ≥ 1 satellite with proxy sensors (CO, NO_2, CO_2/CH_4 Lidar)
- Resampling Frequency: Three (or more) GEO satellites to monitor diurnally varying processes over continents
  - Europe/Africa, North/South America, and East Asia
- Infrastructure: A calibration, validation, and flux inversion modeling infrastructure to integrate space and ground based observations to yield reliable GHG fluxes

GCOS CO_2 and CH_4 Requirements.

The 2011 update for the Global Climate Observing System (GCOS) Systematic Observation Requirements for Satellite-Based Data Products for Climate (GCOS, 2011) and GCOS 2016 Implementation Plan (GCOS, 2016) included CO_2 and CH_4 measurement requirements

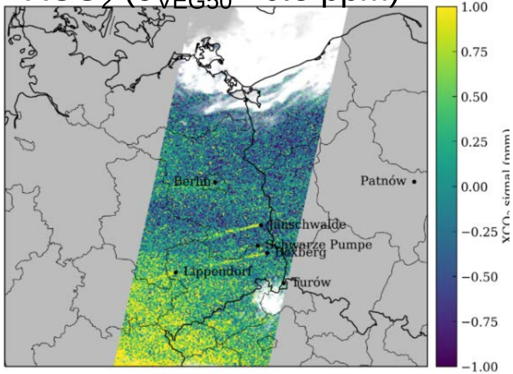
Variable / Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability/ Decade*	Stability/ Decade**
Tropospheric CO_2 column	5-10km	N/A	4 h	1 ppm	0.2 ppm	1.5 ppm
Tropospheric CO_2	5-10 km	5 km	4 h	1 ppm	0.2 ppm	1.5 ppm
Tropospheric CH_4 column	5-10 km	N/A	4 h	10 ppb	2 ppb	7 ppb
Tropospheric CH_4	5-10 km	5 km	4 h	10 ppb	2 ppb	0.7 ppb
Stratospheric CH_4	100-200 km	2 km	Daily	5%	0.30%	0.30%

These requirements are ideal, but were adopted as initial targets for the constellation

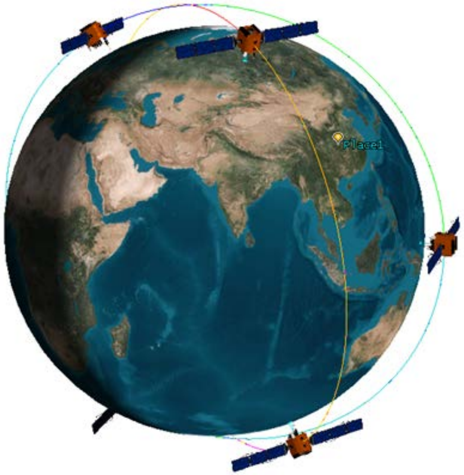
* from GCOS 2011
** from GCOS 2016

Future LEO GHG Constellations in the Planning Stages

- Copernicus CO_2 Sentinel (2025+)
  - 3 or 4 LEO satellites in an operational GHG constellation
  - Primary instruments measure O_2 (0.76 μm A-band), CO_2 (1.61 and 2.06 μm), and NO_2 (0.450 μm) at a spatial resolution of 2 km x 2 km along a broad (200-300 km) swath
  - A dedicated cloud/aerosol instrument is also under consideration



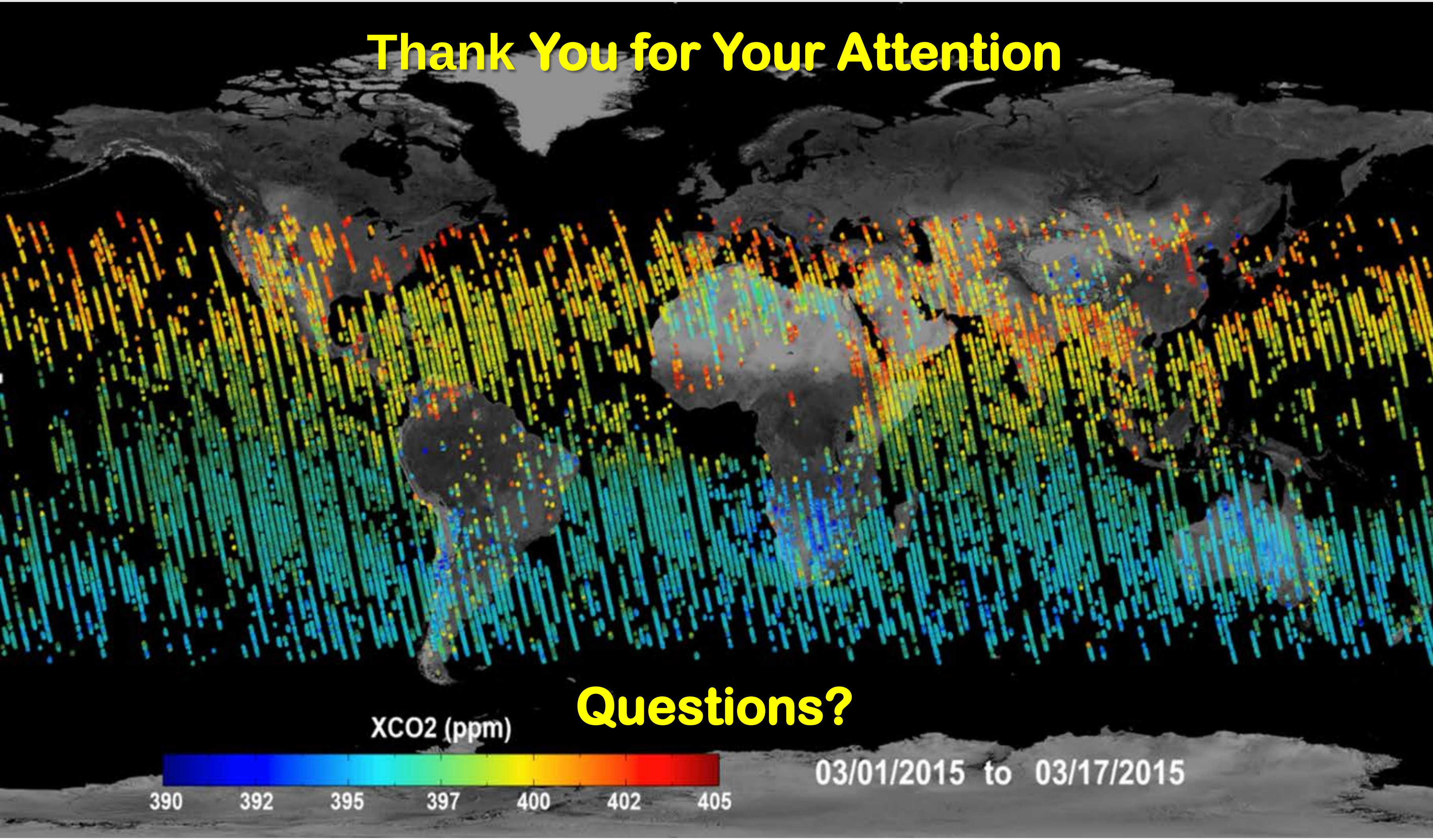
- TanSat-2 Constellation
  - 6 satellites, with 3 flying in morning sun-synchronous orbits and 3 flying in afternoon sun-synchronous orbits
  - primary GHG instrument on each satellite with measure CO_2 (1.61 and 2.06 μm), CH_4 and CO (2.3 μm) as well as the O_2 A-band (0.76 μm) across a 100-km cross-track swath



TanSat Constellation

Summary

- Space-based remote sensing observations hold substantial promise for verifying inventories
  - These data complement existing ground-based and aircraft based in situ data with increased coverage and sampling density
- Over the next decade, a succession of missions with a range of CO_2 and CH_4 measurement capabilities will be deployed
  - These missions are demonstrating the precision and resolution needed to monitor inventories, but improvement in accuracy and coverage needed to for this application
  - Much greater benefits could be achieved if these sensors can be cross-calibrated and their products can be cross-validated so that they can be combined into a long, continuous GHG data record
- Well coordinated constellations of GHG satellites, combined with improved ground and aircraft-based data and flux inversion modeling tools could meet the expanding needs for independent verification of GHG inventories


Thank You for Your Attention
Questions?
XCO2 (ppm)
390
392
395
397
400
402
405
03/01/2015 to 03/17/2015